THE ASTROPHYSICAL JOURNAL, 542:L147–L150, 2000 October 20

SECONDARY FRAGMENTATION OF THE *SOLAR AND HELIOSPHERIC OBSERVATORY* SUNGRAZING COMETS AT VERY LARGE HELIOCENTRIC DISTANCE

ZDENEK SEKANINA
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109; zs@sek.jpl.nasa.gov
Received 2000 August 4; accepted 2000 August 21; published 2000 October 3

ABSTRACT

The temporal distribution of the Kreutz group of sungrazing comets has been known to have an episodic character on timescales from weeks to tens of years. With the large number of minor members of this group being nowadays discovered in images taken with the *Solar and Heliospheric Observatory* coronagraphs, it has become apparent that the distribution of these faint comets is episodic on a much shorter timescale, with objects arriving in pairs during a small fraction of a day. It is shown that the rate of these pairs is much too high for a random sample. Their existence is readily explained as a result of secondary, low-velocity, nontidal fragmentation episodes, which occur virtually spontaneously at very large heliocentric distances and involve the products of near-perihelion splitting of progenitor fragments during their previous return to the Sun. In fact, the pairs are merely extreme manifestations of larger clusters of such subnuclei, with a complex hierarchy of fragments. Each cluster is an outcome of a sequence of nontidal fragmentation events, which begins—after the initial tidal breakup—at some point along the outbound leg of the orbit and then continues episodically to and past aphelion. A similar scenario of posttidal progressive disintegration was firmly established for comet Shoemaker-Levy 9, based on extensive observations of its secondary and tertiary nuclei during many months preceding the comet's collision with Jupiter. Also, there are similarities with the mechanism proposed recently for the formation of striations in the dust tail of comet Hale-Bopp, and a logical extension of this process is the evolution of comet dust trails.

Subject headings: comets: general — methods: data analysis

1. INTRODUCTION

The arrival of three (and possibly four) comets between 1880 and 1887 moving about the Sun in very similar and highly unusual, sungrazing paths was undoubtedly the decisive stimulus that made H. Kreutz begin his study of their orbits. Two results of his extensive investigation (Kreutz 1888, 1891, 1901) should be mentioned here. (1) He offered a proof that none of these comets had been a reappearance of the great comet of 1843, as speculated by many at the time; and (2) he found that the string of several nuclei observed in the sungrazer 1882 II = C/1882 R1 over a period of many months after perihelion represented the early evolution of new comets that would return to the Sun at times spanning a few centuries, even though their orbits are essentially identical in the inner solar system.

There was a long period of drought, with only one member of this group discovered in the next 75 yr. Between 1963 and 1970 came another shower of three comets. The last one, comet 1970 VI = C/1970 K1, remains to this day the most recent sungrazer seen from the ground. Even before its arrival, Marsden (1967) identified two distinct subgroups, and it became apparent that the temporal distribution of these objects is highly uneven on a timescale of tens of years.

Thanks to the spaceborne Solwind coronagraph on the *P78-1* satellite and, subsequently, another coronagraph on the *Solar Maximum Mission* (*SMM*), the number of known members of what has become known as the Kreutz group of sungrazing comets was increased by 16 in 10 yr, between 1979 and 1989. These discoveries showed that the temporal distribution is also episodic on timescales as short as weeks or even days (Marsden 1989). In addition, MacQueen & St. Cyr (1991) mentioned that no sungrazing comets were detected between 1973 May and 1974 February with the *Skylab* coronagraph, whose design was similar to that of the *SMM* instrument. This negative result contrasts with five sungrazers detected with the *SMM* coronagraph between 1988 May and 1989 February.

2. DISTRIBUTION OF THE *SOHO* SUNGRAZERS

Following the launch of the *Solar and Heliospheric Observatory* (*SOHO*) mission on 1995 December 2, the number of newly discovered members of the Kreutz group began to skyrocket, approaching 200 at the time of this writing. Although the first report of a *SOHO* discovery was not published until almost 1.5 yr after the launch (St. Cyr 1997), it was later announced that the *SOHO*'s earliest sungrazer, C/1996 B3, was detected in frames taken in late 1996 January (Brueckner 1997) with one of the three instruments (C1, C2, and C3) of the Large Angle and Spectrometric Coronagraph experiment that is imaging the corona in white light out to ∼30 $R_\odot$ (Brueckner et al. 1995). The C2 and C3 coronagraphs have provided almost all the data on the *SOHO* sungrazing comets.

An updated chronological list of the *SOHO* sungrazing comets is being maintained by D. A. Biesecker (2000),[1] who has called attention to numerous cases of comet *pairs*, mostly in May or June, with two objects arriving at the Sun nearly at the same time. In this Letter, I define a pair, rather arbitrarily, as two sungrazers that pass through perihelion within not more than 0.5 days. Inspection of Biesecker's data indicates that currently there are 15 pairs in his list, as summarized in Table 1. The members of each pair are presented chronologically, so that the difference ΔT in the time of perihelion passage of the second member relative to the first is always positive. Also shown are the date(s) of the pair's perihelion passages and the reference to the Minor Planet Electronic Circular (MPEC)[2] with the relevant astrometric and orbital data. Comparison of the ΔT intervals with expected rates predicted from the Poisson distribution suggests that a random sample must have ∼200 entries to explain one pair, ∼15,000 entries to explain two pairs,

[1] Electronic bulletin board; available at http://sungrazer.nascom.nasa.gov.
[2] B. G. Marsden 2000, electronic page of the IAU Minor Planet Center; available at http://cfa-www.harvard.edu/mpec/RecentMPECs.html.

TABLE 1
LIST OF COMET PAIRS AMONG *SOHO* SUNGRAZERS[a] (PERIHELION PASSAGES ≤0.5 DAYS OF EACH OTHER)

Pair	*SOHO* Sungrazers	ΔT (day)	Date(s)[b] (UT)	Reference (MPEC)[c]
1	C/1998 K9, K15	0.04	May 29	1999-A25, 2000-M32
2	C/1997 J3, J4	0.09	May 10	2000-P18
3	C/1998 K10, K11	0.18	Jun 1/2	1999-A26, 1999-A27
4	C/1999 K9, K13	0.20	May 24	1999-M08, 2000-L53
5	C/1999 O1, O3	0.24	Aug 1	2000-C59, 2000-E29
6	C/2000 L2, L3	0.27	Jun 10	2000-L57, 2000-L58
7	C/1999 L6, L4	0.32	Jun 1/2	2000-N26, 1999-M10
8	C/1997 K4, K1	0.34	Jun 1	2000-P18, 1997-L02
9	C/1999 K10, L6	0.35	Jun 1	1999-M09, 2000-N26
10	C/1999 J8, J1	0.37	May 8	2000-L47, 1999-J29
11	C/2000 M1, M2	0.40	Jun 18	2000-M35, 2000-N17
12	C/1998 L5, L6	0.41	Jun 5/6	2000-N25
13	C/1999 S5, S6	0.41	Sep 21	2000-F10, 2000-F11
14	C/1998 L4, L5	0.45	Jun 5	2000-N25
15	C/1999 K12, K9	0.50	May 23/24	2000-L52, 1999-M08

[a] As of 2000 August 4.
[b] Year defined by the sungrazers' designations in the second column.
[c] See footnote 2.

~500,000 entries to explain three, etc. Thus, only one pair could be compatible with a random set. In their total, the pairs are not fortuitous groupings of objects and there must be a physical reason for their existence. To solve this puzzle is the prime objective of this study.

3. SECONDARY FRAGMENTATION

Nuclear fragmentation has long been popular as an explanation for the Kreutz sungrazing group, but it has been traditionally assumed that splitting always occurs at, or very close to, perihelion. This is not surprising, because at least two (and possibly three) Kreutz sungrazers displayed multiple nuclei shortly after perihelion, with both the Sun's tidal force and the extremely hostile environment of the solar corona providing good candidates for the trigger mechanism. Near-perihelion splitting was also the driving idea behind Marsden's (1967, 1989) bold effort aimed at establishing the Kreutz group's membership hierarchy. On the other hand, most comets that are known to have split did so nontidally (e.g., Sekanina 1982), and it has been recognized that there are major differences between the behavior of the products of tidal and nontidal fragmentation (Sekanina 1997).

The troublesome issue of unexpectedly short intervals between many members of the Kreutz sungrazing group is not new. Marsden (1989) was well aware of the same problem among the objects discovered with the *SMM* coronagraph, some of which arrived less than 2 weeks apart. This interval is much too short by more than 3 orders of magnitude relative to the orbital period differences of 100–200 yr calculated for the freshly formed fragments of the major sungrazers, C/1882 R1 (Kreutz 1891) and C/1965 S1 (Marsden 1967). The temporal separation for the tightest *SOHO* pair in Table 1 is fully 6 orders of magnitude shorter!

An effort to explain the short intervals between Kreutz sungrazers and especially the existence of the pairs by extremely low differential nongravitational decelerations acquired at a tidal breakup at previous perihelion is futile and meaningless. In fact, the perihelion distances of the members in 13 among the 15 pairs in Table 1 differ enough to rule out their breakup at perihelion. A scenario that avoids this contradiction involves the process of *secondary fragmentation*, described in detail by Sekanina, Chodas, & Yeomans (1998) in their study of the evolution of nuclear fragments of comet Shoemaker-Levy 9 (D/1993 F2). These authors showed that most of the 25 investigated fragments were products of discrete episodes of *nontidal* fragmentation. These events occurred more or less randomly over a period of 9 months or more after the encounter with Jupiter in 1992 July and were manifestations of a continuing, virtually spontaneous disintegration (possibly assisted by rotational and/or thermal stresses) of the masses that survived the tidal breakup intact but structurally weakened by extensive cracks inflicted by the tides during the close encounter. A similar scenario obviously also applied in the case of comet 16P/Brooks 2 following its close approach to Jupiter in 1886 (see Sekanina 1977, 1978). Thus, episodic nontidal splitting appears to commonly follow tidal splitting, leading to a complex hierarchy of fragments (secondary, tertiary, etc.) whose number is ever increasing—while their size is decreasing—with time.

4. ORBITAL SOLUTIONS FOR THE *SOHO* PAIRS

To test this proposed scenario for the *SOHO* sungrazers, I first inspected the relevant MPECs (Table 1) to find astrometric observations of both members of a given pair in the same C2 and/or C3 coronagraph frames so that I could determine directly the positional separations of the two objects, i.e., their offsets in right ascension and declination, at any given time. It turned out that of the 15 pairs of sungrazers in Table 1, only four satisfied this condition: pair 1, with seven frames; pair 2, with six frames; pair 3, with 34 frames; and pair 5, with 14 frames. Since the task is to determine a relative motion, one of the two objects is to be used as a reference point. It makes no difference which is selected, but either the leading or the persistently brighter one (if that is the case) was generally the choice in past practice.

Since the published astrometric observations are in the *SOHO*-centric coordinate system, it was necessary first to convert the offsets into the geocentric coordinate system before the author's standard model for the split comets (Sekanina 1978, 1982) could be applied. Using the available geocentric coordinates of the *SOHO* spacecraft, this transformation was accomplished by rigorously calculating, for each observation time, the differences between the geocentric and *SOHO*-centric offsets from the sets of orbital elements for the pair and by applying the derived corrections to the observed *SOHO*-centric offsets.

Once the pair's geocentric offsets were derived, the application of the model offered a choice to solve for up to five parameters: the time of splitting, the RTN components of the separation velocity (i.e., radial, transverse, and normal in the coordinate system referred to the orbit plane and aligned with the comet-Sun direction), and the differential nongravitational deceleration. The procedure involves a least-squares, differential-correction, iterative algorithm that searches for an optimized solution. An extremely helpful feature is the option to solve for any combination of fewer than the five unknowns, so that altogether $2^5 - 1$, or 31, different versions of the code are available. This option turned out to be vitally important on numerous occasions during the present calculations, as the convergence was sometimes slow and the number of unknowns in the procedure could often be increased by not more than one at a time.

I began my orbital calculations with the pair of C/1998 K10 and C/1998 K11 because it provided the largest data set. The two objects were simultaneously under observation for more than 1.5 days, during which time their separation increased from 27′ to 43′. While the observed orbital arc warranted the calculation

TABLE 2

SUM OF SQUARES OF RESIDUALS, $\sum (O-C)^2$

Time of Breakup from Perihelion[a]	Distance from Sun (AU)	$\sum (O-C)^2$ (arcsec^2)
−0.01	15	1021.55
−0.02	23	703.35
−0.05	41	522.86
−0.10	61	484.05
−0.1175	67	482.81
−0.15	76	485.54
−0.20	88	495.51
−0.30	104	522.60
−0.40	113	553.77
−0.50	116	589.02
−0.60	113	630.92
−0.70	104	685.09
−0.80	88	765.68
−0.90	61	927.36
−0.95	41	1139.18
−1.00	0.0058	[b]

NOTE.—From 12 offsets in optimized solutions for pair C/1998 K10, K11 ($e = 0.9999$) as a function of assumed breakup time.

[a] Units of orbital period, assumed to be 442 yr.

[b] No converging solution was found.

of only parabolic elements for either object,[3] the major members of the Kreutz group are known to have orbital periods on the order of a few hundred to ∼1000 yr. Thus, solutions for the pair's breakup were searched for on two assumptions regarding the orbit eccentricity of the reference object C/1998 K10, 0.9998 and 0.9999, implying orbital periods of 156 and 442 yr, respectively. The first assumption would make the object's previous return to the Sun nearly coincident with the arrival time of the celebrated sungrazer 1843 I = 1843 D1.

Experimentation with the astrometric data for this pair showed large residuals left by most of the 34 pairs of offsets, suggesting that the positional measurements were difficult. Only 12 pairs of offsets were eventually used, yielding residuals consistently smaller than $\pm 10''$. However, no converging five-parameter solution was found, regardless of whether the apparently inferior positions were included or removed. The reason was an extremely high correlation between two parameters, the radial component of the separation velocity and the deceleration, an effect of the exceptionally elongated orbit. Thus, equivalent solutions were found as various values were assigned to the deceleration. For example, in runs with the orbital period of 442 yr, an incremental change of 100 units of 10^{-5} the solar attraction in the deceleration (a relatively large effect; cf. Sekanina 1982) entailed a sunward change of only 1.8 m s^{-1} in the radial velocity. The most important property of all these solutions was the separation time's near independence of the deceleration and velocity. With a 442 yr orbital period, this separation time came out nominally to be always close to 53 yr before perihelion, at a heliocentric distance of ∼67 AU, to be compared with the assumed aphelion distance of 116 AU. When the aphelion was moved to 58 AU, the heliocentric distance of the pair's breakup point changed to near 44 AU. Given the large distances involved, I eventually assumed a zero deceleration and searched for optimized four-parameter solutions. There is no question that the breakup of this pair occurred along the inbound leg of the orbit, long *after aphelion*.

[3] B. G. Marsden 1999; MPEC, 1999-A26 and 1999-A27; see http://cfa-www.harvard.edu/mpec/RecentMPECs.html.

The results of the calculations are presented in two tables. The dependence of the quality of least-squares fitting on the choice of the breakup time for the pair of C/1998 K10 and C/1998 K11 is illustrated in Table 2, where the sum of squares of the residuals is presented on the assumption of an eccentricity of 0.9999 (442 yr orbital period).

Table 3 lists the optimized solutions for three pairs. Unlike C/1998 K10 and C/1998 K11, the pair C/1998 K9 and C/1998 K15 is found to have split probably *before aphelion* and not too far from it. The offset residuals for this pair were exceptionally good; for six of the seven frames they stayed well within 3″, and I could afford to eliminate a data point with a residual slightly exceeding 5″. Even though the heliocentric distance at splitting depends strongly on the assumed eccentricity, the relative location of the point of breakup is fairly well determined and the branch of the orbit along which the event occurred (preaphelion vs. postaphelion) is consistently identified by the nominal values of the separation time. The solution for the third pair, C/1999 O1 and C/1999 O3, although somewhat less well determined, also suggests a preaphelion splitting. For the fourth pair, C/1997 J3 and C/1997 J4, the interval of common frames is only ∼0.1 days long and the offsets are very discordant. A derived solution,

TABLE 3

ORBITAL SOLUTIONS FOR THREE PAIRS OF *SOHO* SUNGRAZING COMETS

	C/1998 K10, C/1998 K11		C/1998 K9, C/1998 K15		
PARAMETER	Case 1	Case 2	Case 1	Case 2	C/1999 O1, C/1999 O3
Assumption:					
Orbital eccentricity	0.9998	0.9999	0.9999	0.99995	0.9999
Aphelion distance (AU)	58	116	112	224	102
Orbital period (yr)	156	442	419	1185	364
Conditions at breakup:					
Time from perihelion passage[a]	−0.20 ± 0.10	−0.12 ± 0.08	−0.62 ± 0.23	−0.66 ± 0.23	−0.80 ± 0.23
Nominal Sun's distance (AU)[b]	44 (post)	67 (post)	108 (pre)	209 (pre)	77 (pre)
Separation velocity:					
Total magnitude (m s^{-1})	6.35 ± 1.20	4.21 ± 1.28	5.10 ± 0.70	2.62 ± 0.52	4.18 ± 1.58
Radial component (m s^{-1})	+0.29 ± 0.17	+0.17 ± 0.14	−0.08 ± 0.00_4	−0.03 ± 0.00_1	−0.05 ± 0.02
Transverse component (m s^{-1})	−5.24 ± 1.31	−3.47 ± 1.40	+5.10 ± 0.70	+2.62 ± 0.52	+3.50 ± 1.66
Normal component (m s^{-1})	−3.57 ± 0.91	−2.37 ± 0.97	−0.10 ± 0.03	−0.05 ± 0.02	−2.29 ± 1.39
Number of offset pairs used[c]	12	12	6	6	5
Mean residual (arcsec)	±4.91	±4.91	±1.57	±1.57	±4.56

[a] Units of orbital period. Minus sign indicates reckoning back in time.

[b] Parenthesized term is the location of the nominal point of breakup relative to aphelion, i.e., either preaphelion or postaphelion.

[c] Offset pairs with residuals not exceeding in either coordinate $\pm 10''$ for the pairs C/1998 K10, C/1998 K11 and C/1999 O1, C/1999 O3 and $\pm 3''$ for C/1998 K9, C/1998 K15.

showing that the breakup occurred probably close to aphelion with a separation velocity of ∼7 m s^{-1}, is very poorly defined and is not listed in Table 3.

The radial component of the separation velocity is the parameter that primarily determines the separation between the pair's members along the track and therefore the difference ΔT (Table 1). Its consistently small values in the solutions listed in Table 3 are a result of selecting the pairs with ΔT near zero. Very significantly, this fact implies that the radial velocity component of a few meters per second acquired during a single event of secondary fragmentation can readily accommodate the pair's members arriving at the Sun several days and perhaps even a few weeks apart.

While the quality of the solutions for the four pairs is very uneven, the individual residuals from the positional offsets in right ascension and declination show no systematic trends whatsoever in any of the runs. Thus, the necessary condition for successful least-squares data fitting has always been satisfied.

5. CONCLUSIONS

The principal result of this study is the finding that the pairs among the *SOHO* sungrazers, which arrive at perihelion only a fraction of a day apart, can readily be explained as products of nontidal, low-velocity breakup episodes at very large heliocentric distances. The precursor objects could be products of a tidal splitting near the Sun or of another, subsequent nontidal splitting. Nontidal breakups of nuclear fragments, suffering from extensive cracks inflicted by the Sun's tidal forces during the previous perihelion passage, apparently occur virtually spontaneously either on the way to aphelion or after aphelion. The involved separation velocities of a few meters per second (Table 3) are typical for comet spin velocities and may indicate that nontidal breakups are assisted by tension due to rotation. They may also be aided by thermal stresses, brought about by different temperature gradients on the sunlit side and the dark side, even when the nucleus is in an inert state.

The proposed scenario of a sequence of nontidal fragmentation episodes, which follow a tidal event at perihelion and may extend along much of the orbit about the Sun, is strongly reminiscent of the observed evolution of comet Shoemaker-Levy 9 between its close encounter with Jupiter in 1992 July and its collision with the planet 2 yr later. Based on this experience, it is virtually certain that the pairs of sungrazers are merely extreme manifestations of larger clusters of fragments. If so, then dozens of the *SOHO* sungrazers observed to arrive at the Sun over periods of many days may all be products of numerous nontidal breakup episodes and have the *same parent* that was born one revolution earlier. This scenario is supported by the fact that three sungrazers listed in Table 1 (C/1999 K9, C/1999 L6, and C/1998 L5) are in fact each a member of *two* different pairs. Also, eight of the 15 pairs arrived in June and 13 in May or June. Unfortunately, because of large separations between any two *SOHO* sungrazers arriving more than about 0.3 days apart, it is not possible to image them simultaneously and determine their offsets directly. Thus, one cannot examine the distribution of potential breakup points along the orbit for most members of a cluster directly.

If a cluster of nearly simultaneously arriving *SOHO* sungrazers contains fragments (secondary, tertiary, etc.) of the same progenitor object that is only one revolution about the Sun old, this scenario also applies to those *SMM* sungrazers that Marsden (1989) was concerned with. The process of progressive disintegration has an extension in the evolution of comet dust trails, and low-velocity separation events far from the Sun were recently also proposed (Sekanina et al. 2000) in the context of a model for striations in the dust tail of comet Hale-Bopp (C/1995 O1). For most sungrazers, this process is interrupted by complete sublimation of dust and disintegration of more sizable fragments by the time they reach the next perihelion. In the light of past evidence on cometary splitting, the lesson to be learned from this remarkable experience with the *SOHO* sungrazers is that comets can break up into fragments of all possible sizes anywhere in space and at any time.

This work benefited from my discussions with B. G. Marsden and comments by D. A. Biesecker on a draft of this Letter. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Brueckner, G. E. 1997, IAU Circ. 6669
Brueckner, G. E., et al. 1995, Sol. Phys., 162, 357
Kreutz, H. 1888, Publ. Sternw. Kiel, 3
———. 1891, Publ. Sternw. Kiel, 6
———. 1901, Astron. Abh., 1, 1
MacQueen, R. M., & St. Cyr, O. C. 1991, Icarus, 90, 96
Marsden, B. G. 1967, AJ, 72, 1170
———. 1989, AJ, 98, 2306
Sekanina, Z. 1977, Icarus, 30, 574
Sekanina, Z. 1978, Icarus, 33, 173
———. 1982, in Comets, ed. L. L. Wilkening (Tucson: Univ. Arizona Press), 251
———. 1997, A&A, 318, L5
Sekanina, Z., Boehnhardt, H., Ryan, O., & Birkle, K. 2000, presentation at IAU Colloq., Dust in the Solar System and Other Planetary Systems
Sekanina, Z., Chodas, P. W., & Yeomans, D. K. 1998, Planet. Space Sci., 46, 21
St. Cyr, O. C. 1997, IAU Circ. 6653